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Target Area Studies
Volume I—Combustible Fuel Loads in Nashville, Tennessee

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Standard land use and census data is used to construct a detailed combustible fuel load map for a typical medium-sized U.S. city (Nashville, Tennessee). Our method recognizes eleven land use categories. Each category is assigned fuel loading values based on analyses of the total burnable fuel mass and areal densities of the buildings and vegetation present. We find that the distribution of fuels is non-uniform and highly dependent on the internal structure of the city. The highest fuel load densities (>40 kg/m^2) are found in portions of the city occupied by densely-packed multiple-family residential buildings, liquid fuel storage terminals, and in industrial/commercial complexes. Much lower fuel loads (<5kg/m^2) are found in outlying suburbs and rural areas. This uneven fuel distribution results in a several-fold difference in the net fuel availability for potential urban targets spaced only a short distance apart. We demonstrate that this may in turn strongly influence the intensity of nuclear burst-generated fires, the amount of smoke emitted, and the altitudes to which the smoke is injected.

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PREFACE

This report continues the Pacific-Sierra Research Corporation (PSR) study of the effects of fire generated by nuclear weapons. In this volume, we map the distribution of combustible fuels in a representative medium-sized U.S. city (Nashville, Tennessee). The relation between this distribution and the internal structure of the city is discussed. In Vol. 2, these fuel loads are used to calculate the atmospheric smoke injection for specific urban targets and collateral areas.

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CONVERSION TABLE

Conversion factors for U.S. customary to metric (SI) units of measurement

To Convert From	To	Multiply
angstrom	meters (m)	1.000 000 X E–10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E+2
bar	kilo pascal (kPa)	1.000 000 X E+2
barn	meter^2 (m^2)	1.000 000 X E–28
British Thermal unit (thermochemical)	joule (J)	1.054 350 X E+3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2(MJ/m^2)	4.184 000 X E–2
curie	giga becquerel (GBq)*	3.700 000 X E+1
degree (angle)	radian (rad)	1.745 329 X E–2
degree Fahrenheit	degree kelvin (K)	$t_K = (t^{\circ}f + 459.67)/1.8$
electron volt	joule (J)	1.602 19 X E–19
erg	joule (J)	1.000 000 X E–7
erg/second	watt (W)	1.000 000 X E–7
foot	meter (m)	3.048 000 X E–1
foot–pound–force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E–3
inch	meter (m)	2.540 000 X E–2
jerk	joule (J)	1.000 000 X E+9
joule/kilogram (J/Kg) (radiation dose absorbed)	Gray (Gy)	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E+3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E+3
ktap	newton–second/m^2 (N–s/m^2)	1.000 000 X E+2
micron	meter (m)	1.000 000 X E–6
mil	meter (m)	2.540 000 X E–5
mile (international)	meter (m)	1.609 344 X E+3
ounce	kilogram (kg)	2.834 952 X E–2
pound–force (lbf avoirdupois)	newton (N)	4.448 222
pound–force inch	newton–meter (N·m)	1.129 848 X E–1
pound–force/inch	newton/meter (N/m)	1.751 268 X E+2
pound–force/foot^2	kilo pascal (kPa)	4.788 026 X E–2
pound–force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound–mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E–1
pound–mass–foot^2 (moment of inertia)	kilogram–meter^2 (kg·m^2)	4.214 011 X E–2
pound–mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 X E+1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E–2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E–4
shake	second (s)	1.000 000 X E–8
slug	kilogram (kg)	1.459 390 X E+1
torr (mm Hg. 0°C)	kilo pascal (kPa)	1.333 22 X E–1

*The becquerel (Bq) is the SI unit of radioactivity; Bp = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

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INTRODUCTION

Cities contain large amounts of combustible material. The wood, plastic, paper, cloth, and asphalt used in the structure and contents of most buildings, together with the oil and gasoline distributed throughout the urban complex, represent a concentrated fuel source which, if ignited, could inject enormous quantities of smoke into the atmosphere. Nuclear weapons provide an efficient incendiary trigger for city fires. It is estimated that a full-scale nuclear attack against the U.S. would yield approximately 40 Tg of smoke, primarily from urban targets [Small, Bush, and Dore, 1989]. Yet many of the specifics about this urban smoke (e.g., the net particulate mass, its optical properties, and the altitudes to which it is injected) are highly uncertain. These uncertainties result from arbitrary assumptions regarding the amount, type, and distribution of combustible fuel loads in urban areas.

Most nuclear winter studies have characterized the fuel loading in cities by a single overall average value. These values are derived either from statistics of the production, consumption, and accumulation of flammable materials [Crutzen, Galbally, and Brühl 1984; Bing, 1985] or from limited surveys of the fuel loads in various building types in U.S. cities [Federal Emergency Management Agency, 1982; Turco et al., 1983; National Research Council, 1985]. In the latter approach, each building type is assigned to one of several functional categories (city center, suburban residential, etc.). A highly idealized model of the geographical distribution of these urban subdivisions (such as the zonal or "concentric ring" model) is then used to average the survey data over the entire city. The resultant weighted mean is assumed to be representative of all U.S. cities, and is often applied to European and Soviet cities as well.

But cities are not all alike. Even cities which appear similar according to the conventional measures of rank (population, population density, built-up area fraction) may be quite different from the standpoint of fuel loading. This city-to-city variation is linked to differences in urban land use—the relative fraction of a city devoted to residential, commercial, and industrial purposes. Each category is characterized by a particular building type and density. The amount of flammable material within structures is also dependent on land use. (For example, industrial warehouses contain more fuel per unit area than most commercial establishments, and both are more heavily loaded than residential structures.) To some extent, the fraction of an urban area occupied by each land use category is a function of geographical region—at least within the U.S. [Bush and Small, 1987]. But considering the diversity of city types in the U.S. (and the even greater differences between U.S., European, and Soviet cities), it is unlikely that a single generic model of urban structure could accurately represent all cities. Likewise, it is doubtful that a single "real" city could serve as a good model for all others. Yet the correlation between fuel loading and land use suggests a formal method for estimating fuel loads in real cities.

Another characteristic of cities is their highly uneven internal distribution of land use types (and, therefore, of fuel loads) which results from their unique topography, historical development, and socioeconomic growth. This lack of uniformity is important in evaluating the fuel loads associated with a given targeting scenario. If, for example, the ignition zone around a particular urban target contains mostly industrial land or a heavily developed central business district (CBD), the fuel loading in the area burned could be far greater than the areal average value for that city. More smoke would be produced and, because the fires would likely be very intense, the plume would reach higher into the atmosphere and contain a greater elemental carbon (soot) fraction. On the other hand, another target zone in the same city might encompass mostly low density suburbs, park land, or even water. The smoke injection there would be relatively minimal. Again, land use is the primary determinant.

In this report we present a calculation of the fuel load for Nashville, Tennessee, and the surrounding area. Our basic data set consists of fuel load estimates for 11 land use categories (five urban and six nonurban). These estimates are derived from extensive surveys of the structure, contents, and densities of buildings across the United States. Census data are used to weight residential building densities within Nashville. These fuel load estimates are then combined with the cartographic land use data. The result is a composite fuel load map for metropolitan Nashville. Since our approach relies on readily available land use and demographic data, it is more generally applicable than those used in previous fuel load estimates for individual cities (e.g., Bracciaventi, Feldman, and Newman, 1968, for Detroit; Simonette et al., 1986, for San Jose). These calculations were based on surveys of *all* structures within the areas studied. This approach, though detailed, cannot be easily extended to other cities. On the other hand, our approach can be readily applied to any U.S. metropolitan area. We present our Nashville calculation as an example.

In Sec.2, we describe the physical geography and land use characteristics of the metropolitan Nashville area. In Sec. 3, we discuss our methodology for computing fuel loads from land use data and present a fuel load map for Nashville. In Sec. 4, we choose several potential targets, demonstrate the sensitivity of fuel loading to target position, and discuss the implications for smoke emission and plume injection altitudes. Conclusions are presented in Sec. 5.

SECTION 2

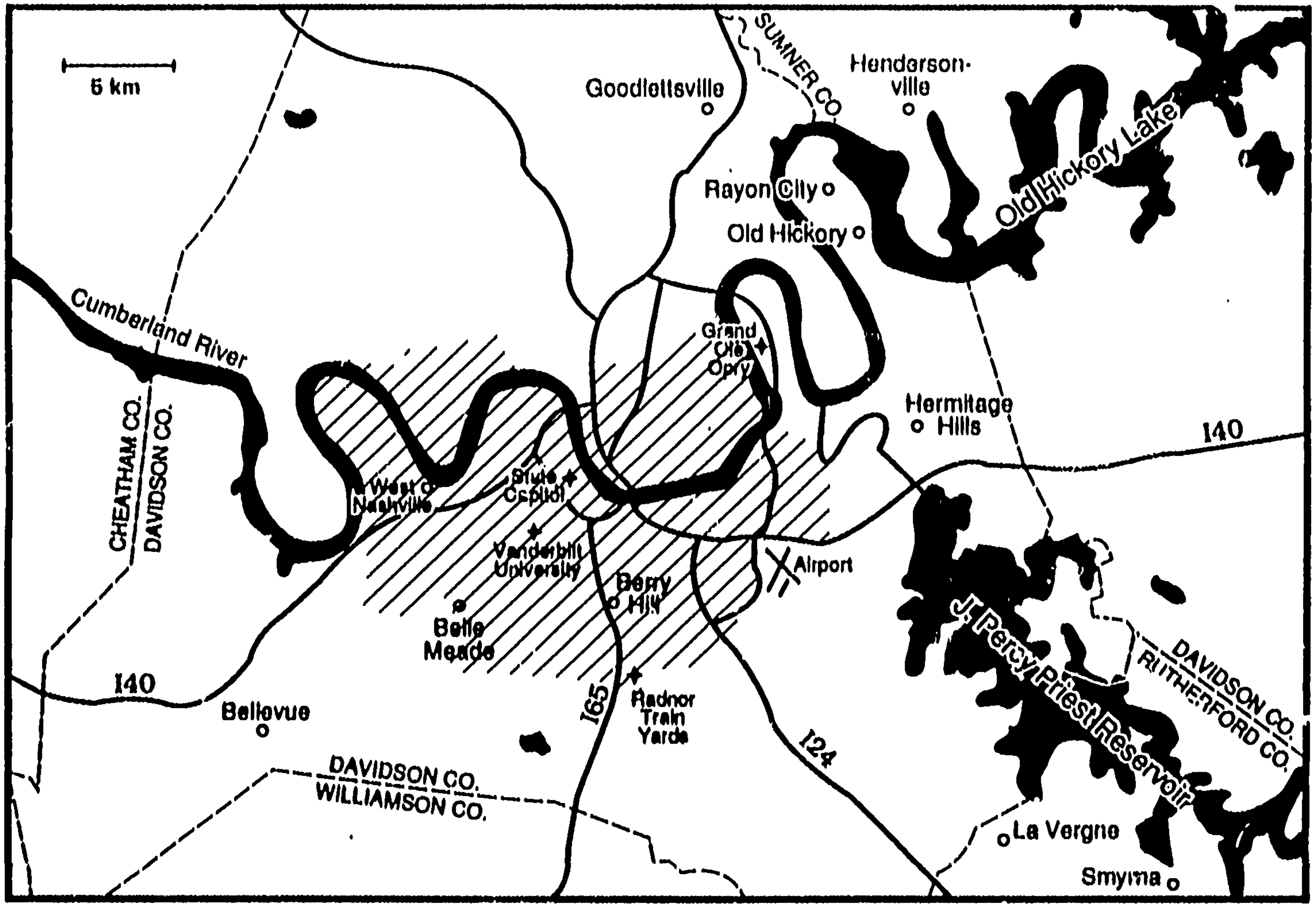
NASHVILLE: GEOGRAPHY AND LAND USE

2.1 GENERAL DESCRIPTION.

Nashville is located on the Cumberland River in north-central Tennessee. It is the state capital and the center of a large metropolitan area that encompasses most of Davidson County. as well as parts of neighboring Williamson. Wilson. Sumner. Cheatham. and Rutherford counties (Fig. 1). It is the 26th largest U.S. city. with an estimated population (as of July 1986) of 473.670 [U.S. Bureau of the Census. 1988]. Perhaps best known as the center of the country music industry (it is the home of the Grand Ole Opry). Nashville also serves as the headquarters for several large finance. insurance. and publishing companies. Leading industries include printing. record production. and the manufacture of clothing. shoes. glass. heating and cooking equipment. and tires. In addition. two automobile plants are located nearby: the Nissan assembly plant in Smyrna. and the General Motors Saturn plant in Spring Hill (about 50 km south of downtown). The area is served by three major highways. Interstates 24. 40. and 65. which intersect near downtown and loop around the CBD: several railroad lines (it is a major regional railroad center): and Nashville Metropolitan Airport. an American Airlines hub. Nashville is also the location of sixteen colleges and universities. the most notable of which include Vanderbilt and Fisk Universities.

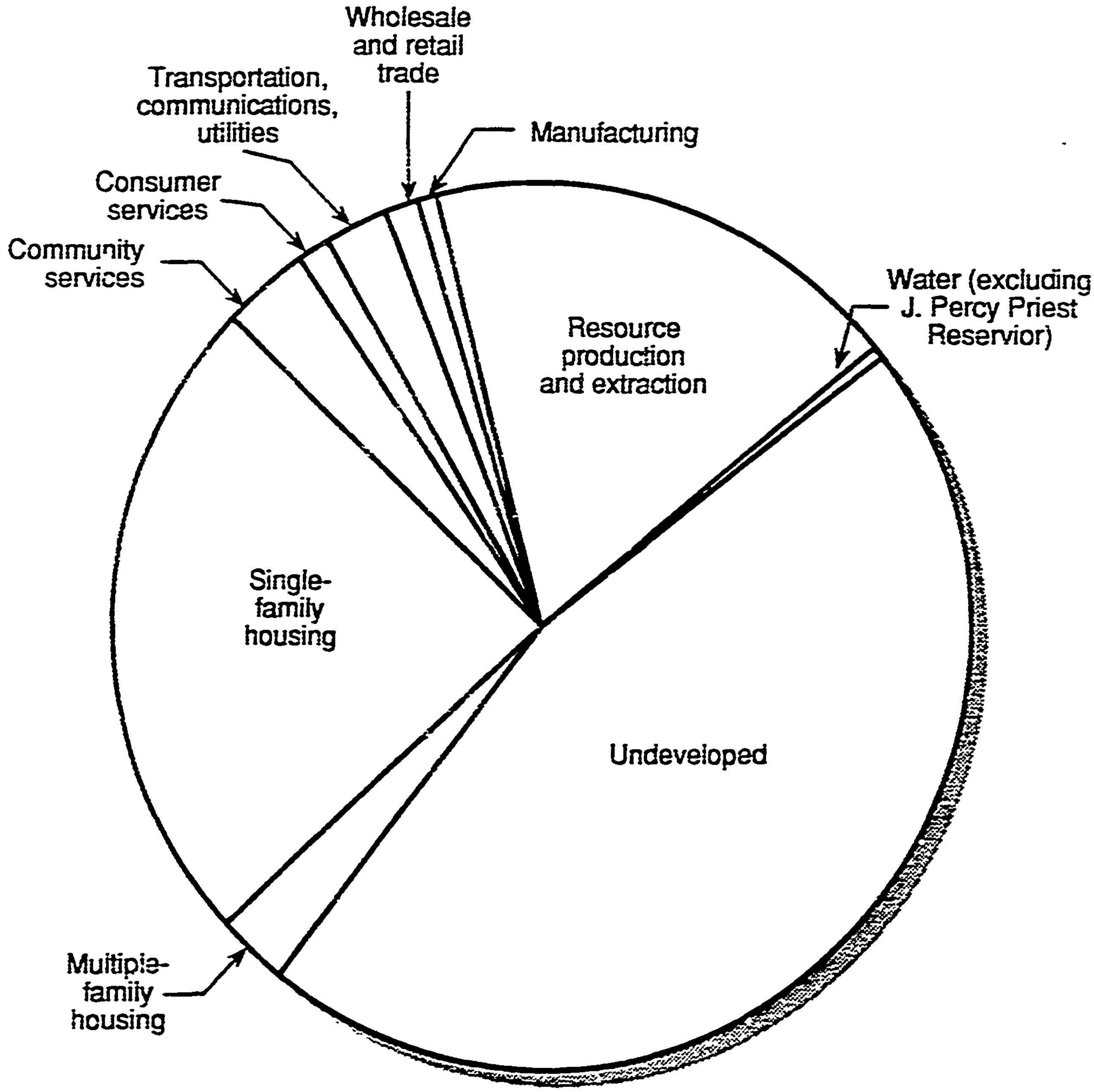
Nashville is situated in the northwest corner of a large lowland region known as the Nashville Basin. The terrain consists of gently rolling land punctuated by small rounded hills. or knobs. To the west and north. a chain of low. highly dissected hills frames the city. Most of Nashville lies on the south bank of the Cumberland River. which makes a series of wide meandering loops as it flows through the region. About 40 km upstream from the city center. Old Hickory Dam blocks the river and forms a large slack-water lake. Another. even larger man-made lake. the J. Percy Priest Reservoir. lies on the Stones River southeast of the city. The dam and two lakes (created in the 1930s by the Tennessee Valley Authority) supply metropolitan Nashville with most of its electrical power and are the focus of much of its recreational activities.

Davidson County and the city of Nashville form a single political entity. The governing unit. known as the Nashville Metropolitan Government. has been widely regarded as a major innovation in local government since its inception in 1963 Its county-wide jurisdiction has made it possible to extend urban services such as sewage disposal far beyond the original city limits. and has contributed to the rapid growth of outlying suburbs. Yet. as shown by Fig. 2. about two-thirds of Davidson County is still rural. In addition. the county encompasses several communities (e.g.. Goodlettsville. Berry Hill) which. although under the jurisdiction of the metropolitan government and usually lumped together with Nashville for census purposes. are actually distinct cities. In this report we therefore distinguish between Nashville proper (an arbitrary division which includes most of the central built-up area) and Davidson County (the wider political unit). The outline of Nashville proper is shown in Fig.1.



Note: Shading indicates Nashville proper.

Figure 1. Metropolitan Nashville, Tennessee.



Source: Metropolitan Planning Commission [1983].

Figure 2. Land-use summary, Nashville-Davidson County.

2.2 LAND USE.

Residential land occupies 49 percent of the urban area within Davidson County (Fig.2). (By comparison, in U.S. cities with populations greater than 100,000, the average is 41 percent [Northam, 1979].) Figure 3, produced from United States Geological Survey (USGS) digital land use data, shows the distribution of land areas devoted primarily to residential purposes. Most of the residential land is concentrated within Nashville proper in two zones located southwest and northeast of downtown. Other concentrations are found in the Goodlettsville area, along the northern shores of Old Hickory Lake (Hendersonville), and in the cities of La Vergne and Smyrna. Smaller rural centers are found throughout the remainder of the metropolitan area.

The distribution of residential land in Nashville strongly reflects the historical development of its transportation network. In this sense it is typical of any large U.S. city of similar age [Bush and Smal', 1987]. Founded in 1779 as a military outpost (Fort Nashborough), Nashville quickly became established as a major riverport. For nearly a century, river traffic dominated the development of the young city, and, as a result, population, commerce, and industry grew mainly north and south along a line paralleling the Cumberland. Residential and commercial zones were not well differentiated during these early years, with retail businesses scattered among residences within a few city blocks of the river [Marshall, 1975]. This pattern continued even into the 1850s with the coming of the railroads and the development of a more diversified economy. Indeed, significant expansion of residential Nashville did not begin until the 1890s, when the streetcar (and, later, the automobile) made quick transportation to and from the crowded central city possible. Two growth patterns emerged at this time [Marshall, 1975]: (1) linear or sectoral growth along the main thoroughfares extending southwest and northeast from downtown, and (2) discontinuous growth associated with the establishment of the first outlying "job-oriented" suburbs (e.g., West Nashville, Old Hickory, and the area around the Radnor Train Yards). Thus, downtown Nashville was gradually abandoned as a residential center, thereby setting the stage for the development of the CBD and the present-day suburban sprawl.

Today, residential Nashville continues to expand at a rapid rate. According to statistics compiled by the Metropolitan Planning Commission (MPC), this growth is occurring primarily in outlying areas along the interstate highways [MPC, 1986]. Interstate 40 is a particular focus of this expansion: most residential building permits issued in recent years have been for districts along this highway, from Bellevue on the west to Hermitage Hills on the east (see Fig. 1). This commuter-oriented growth pattern is typical of suburban expansion in modern U.S. cities [Northam, 1979].

Another indication of the suburban character of residential Nashville is the dominance of single-family detached (SFD) homes over multiple-family (MF) housing structures. Only 15 percent of all the residential structures in Davidson County are MF, and these account for less than 10 percent of the total residential land area (see Fig. 2 and MPC, 1987). (The average for all U.S. cities with populations greater than 250,000 is 17 percent [Northam, 1979].) The areal density of SFD homes by census tract is shown in Fig. 4. Note that the highest densities are found in the older residential zones immediately adjacent to the city center and in West Nashville, while the lowest densities are found in the newer, more affluent outlying suburbs. The distribution of MF structures (Fig. 5)

Figure 3. Residential land, metropolitan Nashville.

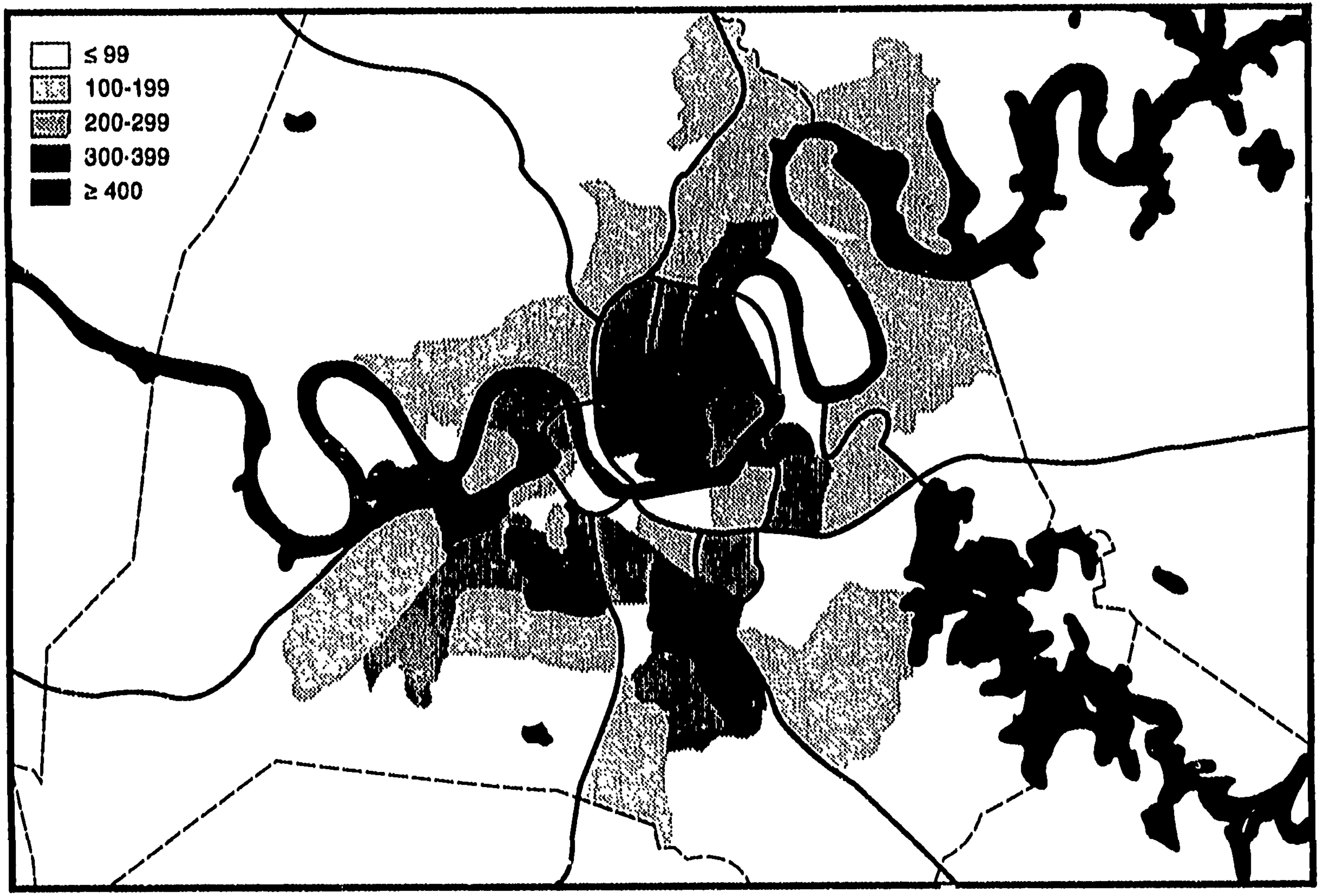


Figure 4. Single-family housing density (structures per square kilometer).

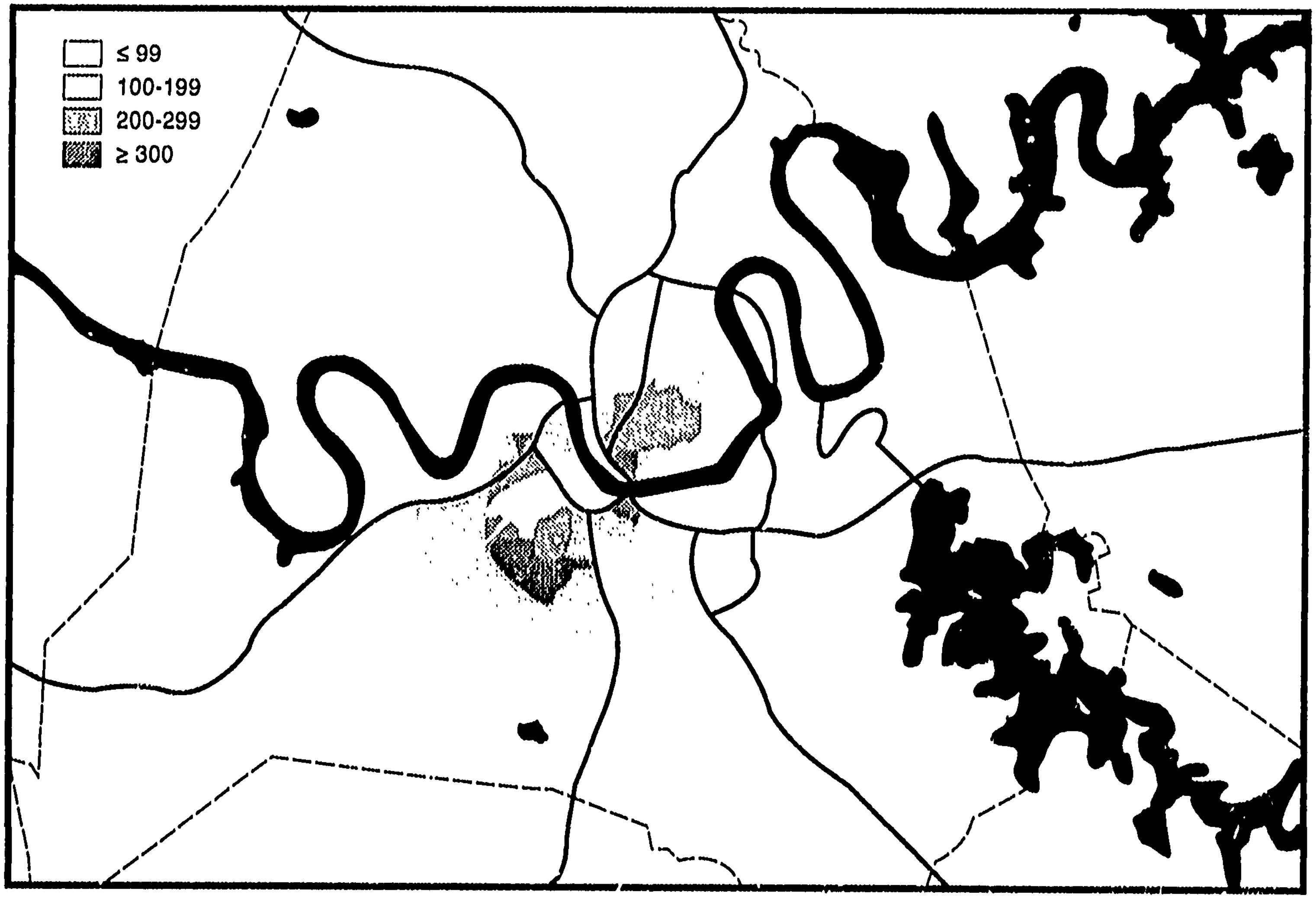


Figure 5. Multiple-family building density (structures per square kilometer).

shows a similar pattern, although the densities are lower. The distribution of structure types is important, since it determines the distribution of fuel loads in residential zones.

Industrial zones and commercial/service districts also display definite distribution patterns. The most prominent industrial areas are clustered along the Cumberland River, mainly close to downtown (Fig. 6). Several large industrial parks are also present; the largest are near Smyrna and in Rayon City near Old Hickory Dam. On the other hand, the distribution of commercial/service areas (which include shopping centers, commercial strips, office buildings, schools, and hospitals) is often more linear. In Nashville (Fig. 7), there are prominent commercial/service strips along major surface streets extending from downtown—a pattern typical of most U.S. urban areas [Bush et al., 1988]. Figure 7 also shows a large downtown commercial zone comprising the heavily developed CBD and Vanderbilt University. There are also commercial zones around the airport, and a large shopping center near Smyrna.

Agricultural land comprises one of the largest land use types in the Nashville area. Figure 8 shows the distribution of cultivated land of all types in the region. Most of the agriculture is confined to somewhat small plots on the relatively flat land east of Nashville proper. West of the city, most of the nonurban land is undeveloped wildland. The only significant agricultural areas here are concentrated along the Cumberland and within the many stream-cut "hollows" which intersect the river valley.

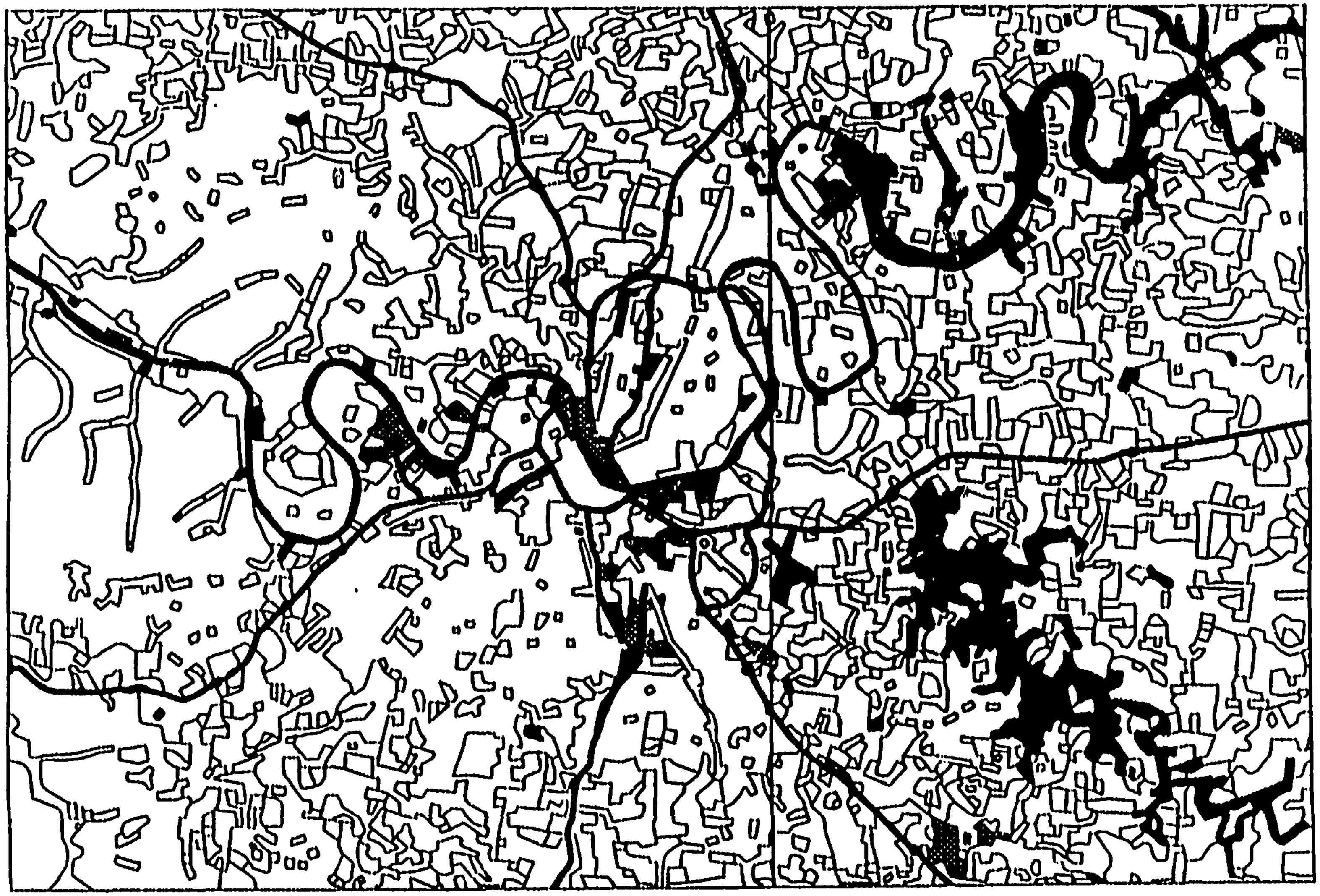


Figure 6. Industrial land, metropolitan Nashville.

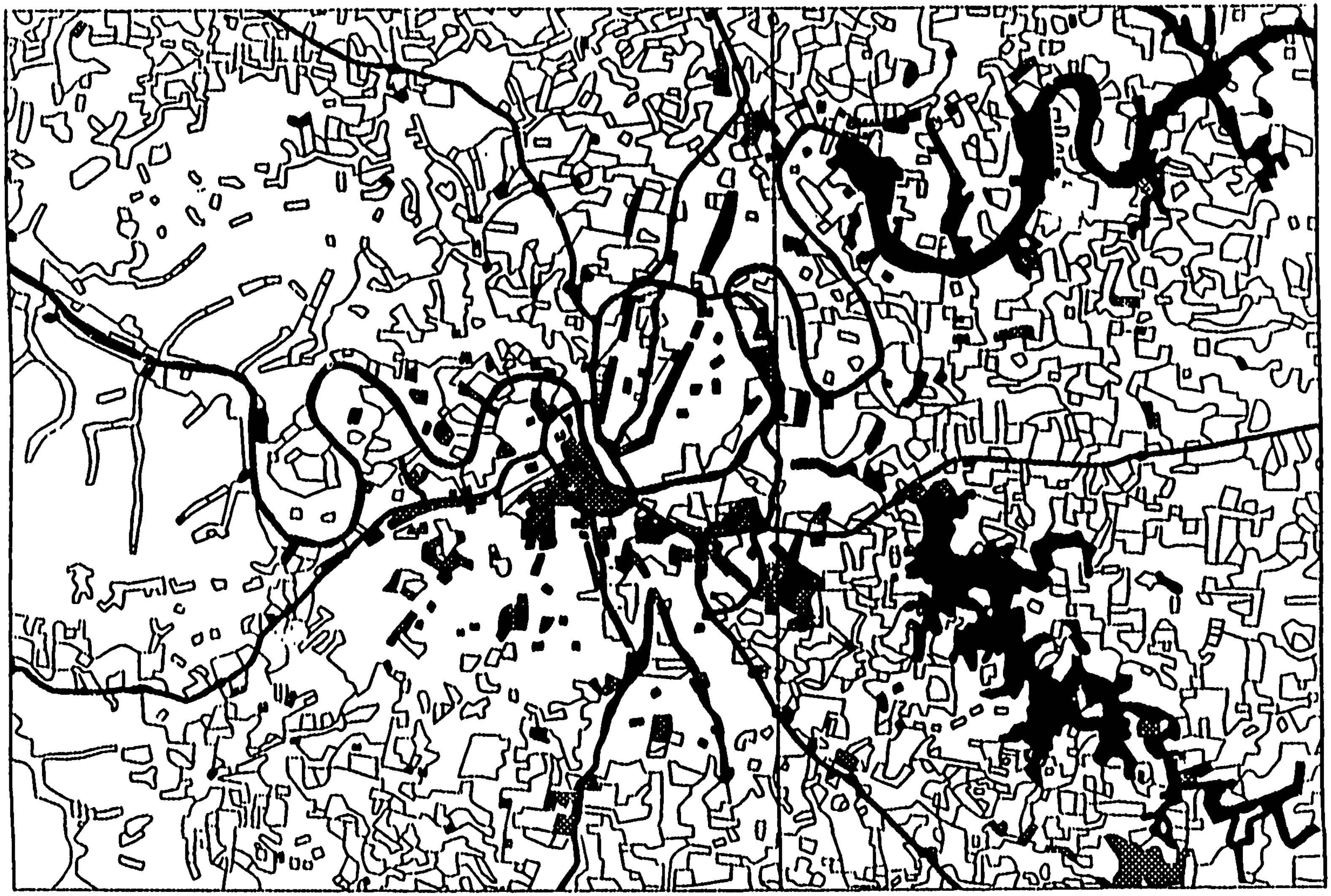


Figure 7. Commercial/service land, metropolitan Nashville.

Figure 8. Agricultural land, metropolitan Nashville.

SECTION 3

FUEL LOAD CALCULATION

3.1 NONRESIDENTIAL LAND.

We assign all land within the metropolitan Nashville area to one of eleven land use categories. These categories, based on the definitions given by Anderson et al. [1976], are listed in Table 1. Also shown are the assumed fuel loads per unit occupied area F, the areal percentages occupied by buildings and vegetation A, and the area-weighted net fuel load densities FD for each category. These values are derived from several sources. For the two main nonresidential urban categories (commercial/services and industrial), we use the structural fuel load and building density estimates derived by Anno et al. [1988]. These estimates are based on analyses of the structure and contents of 33 nonresidential building types (representing over 6000 individual structures) within the United States. Aerial photographs and topographic maps of five representative U.S.urban areas were used to determine building densities. The results represent averages for the entire United States. Although intercity differences no doubt exist, we find that, in general, the variation in nonresidential land use characteristics is small within the U.S. (see Bush and Small, 1987); therefore, these averages are not further weighted in our calculations.

The values for the two remaining nonresidential urban categories (transportation/communication/utilities and other urban) are from Bush et al. [1988]. The designation "other urban" refers to developed portions of the city that include large amounts of open space. Examples include urban parks, golf courses, cemeteries, and zoos [Anderson et al., 1976]. Such areas have low building densities and thus relatively low fuel loads.

Vegetation within cities also contributes to the combustible fuel load. Following Bush et al. [1988], a nominal burnable fuel load per vegetated urban area of 5 kg/m^2, regardless of land use category is assumed. Such loading is at least twice as large as that expected for nonurban vegetation, but is justified by the greater degree of plant desiccation that can occur when vegetation is in close proximity to intense, long-burning structural fires. Blast effects, such as the breaking and scattering of tree limbs and shrubs, are also likely to enhance the amount of burnable vegetation in urban areas.

The Nashville area also includes large portions of nonurban land. We use six nonurban land use categories (Table 1). Fuel loads have been assigned to those categories based on estimates developed by Bush and Small [1985]. For the Nashville region, we assume an agricultural fuel loading appropriate to the predominant crops grown in the area—corn, soybeans, and tobacco. Fuel loads for these crops are seasonal. The crop loading applies to midsummer when the crops are near maturity; in winter the loading is minimal. The fuel load estimates for rangelands and forests also represent summertime conditions. For forests, we choose a value applicable to the deciduous woodland endemic to the Nashville region (comprised mainly of oak, ash, and maple trees). The assumed fuel load for forests is less than one-third the value chosen for agricultural land. This difference results from the higher stand densities and more abundant water supply typical of cultivated land [Bush and

Table 1. Fuel load by land use type in Nashville.

Land Use Type	Fuel Load per Area Occupied $F(kg/m^2)$	Percent Area Occupied A	Net Fuel Load Density FD (kg/m^2)
Urban			
Residential	130 (structures)	7.5 (structures)	
	5 (vegetation)	40.0 (vegetation)	11.7
Commercial, services, and mixed urban	110 (structures)	21.6 (structures)	
	5 (vegetation)	10.0 (vegetation)	24.3
Industrial and mixed	225 (structures)	19.6 (structures)	
	5 (vegetation)	5.0 (vegetation)	44.4
Transportation, communication, and utilities	60 (structures)	5.0 (structures)	
	5 (vegetation)	15.0 (vegetation)	3.8
Other urban	60 (structures)	5.0 (structures)	
	5 (vegetation)	50.0 (vegetation)	5.5
Nonurban			
Agriculture	2.0[a]	70.0	1.4
Rangeland	0.2	100.0	0.2
Forest	0.6[b]	100.0	0.6
Water	0.0	100.0	0.0
Wetlands	0.0	100.0	0.0
Barren	0.0	100.0	0.0

[a] Midsummer value for grain croplands [Bush and Small, 1985].

[b] Summer estimate for deciduous forests [Bush and Small, 1985].

Small, 1985]. Wintertime fuel loads in deciduous forests would be higher by about 30 percent. This follows from smaller live loadings in the forest canopy and greater concentrations of leaves and tinder on the ground.

Given the fuel load per foundation area for nonresidential buildings ($F_{structures}$), the burnable vegetation load per unit area ($F_{vegetation}$), and the mean fractional areas occupied by each ($A_{structures}$ and $A_{vegetation}$), the net nonresidential fuel load density FD is

$$FD = F_{structures} \cdot A_{structures} + F_{vegetation} \cdot A_{vegetation}, \quad (1)$$

where, $F_{structures} = 0$ is assumed for all nonurban categories. The resultant values for FD are listed in Table 1.

3.2 RESIDENTIAL FUELS.

Residential zones comprise the largest fraction of developed land in metropolitan Nashville. Housing types and building densities vary widely across the region and, as a result, so do residential fuel loads. We account for these variations by weighing the densities of both SFD and MF buildings within individual census tracts. For tracts inside Davidson County, we use the housing counts developed by the Nashville-Davidson County Metropolitan Planning Commission [MPC, 1983]; outside Davidson County, residential building densities are estimated from U.S. Census Bureau data [U.S. Bureau of the Census, 1983]. The area-weighted residential fuel load per foundation area for a particular census tract is calculated

$$F_{structures} = \frac{F_{SFD} \cdot A_{SFD} + F_{MF} \cdot A_{MF}}{A_{SFD} + A_{MF}}, \quad (2)$$

where F_{SFD} and F_{MF} are the mean fuel loads per foundation area for SFD and MF structures, respectively, and

$$A_{SFD} = \frac{N_{SFD} \cdot a_{SFD}}{a_{res}} \quad (3)$$

and

$$A_{MF} = \frac{N_{MF} \cdot a_{MF}}{a_{res}} \quad (4)$$

are the corresponding fractional areal building densities. Here N_{SFD} and N_{MF} denote the numbers of SFD and MF buildings within the tract, a_{SFD} and a_{MF} are their mean foundation areas, and a_{res} is the total residential area within the tract (including structures, streets, yards, etc.). Values for N_{SFD}, N_{MF}, and a_{res} are determined uniquely for each census tract, while a_{SFD}, a_{MF}, F_{SFD}, and F_{MF} (Table 2) are assigned values consistent with analyses of the structure, contents, and size of residences throughout the southern U.S. and are assumed not to vary from tract to tract. Some intracity variation in these values no doubt exists, due primarily to differences in land values, socioeconomic status, and historical growth patterns. However, by accounting for residential structure densities (N_{SFD}/a_{res} and N_{MF}/a_{res}) on a tract by tract basis, the most important variations in residential fuel loads are accounted for. Our estimate for a_{MF} (348 m^2), is also assumed invariant within Nashville; it is derived from a statistical analysis of the number of floors and units contained in MF structures built between 1980 and 1984 [U.S. Bureau of the Census, 1985]. This value compares well with the measured mean rooftop area (equivalent to foundation area) of MF buildings (305 m^2) found in a three-city survey [Fretz, n.d.]

Table 2. Residential structure characteristics.

Structure Type	Fuel Load per Foundation Area F (kg/m^2)	Mean Foundation Area a (m^2)
Single-family detached (SFD) homes	115[a]	155[b]
Multiple-family (MF) buildings	167[a]	348[c]

[a]Mean value for southern U.S., from Anno et al. [1988].
[b]From Ransohoff et al. [1987], assuming 68.6 percent of SFD homes in southern U.S. are one story.
[c]U.S. average based on analyses of construction reports (see text).

Using the relation $A_{res} = A_{SFD} + A_{MF}$ in Eq. (2) and applying the result to Eq. (1), FD_{res} is computed for the residential land in each census tract. We find that the distribution of FD_{res} is highly variable, with values ranging from less than 3 kg/m^2 in some outlying areas to over 90 kg/m^2 in the heavily developed MF housing district on the edge of downtown near Vanderbilt University. For Davidson County as a whole, FD_{res} = 11.7 kg/m^2. This is about 20 percent less than the average residential loading for all U.S. cities (15.0 kg/m^2 including vegetation) derived by Anno et al. [1988] and about 20 percent greater than the average for the southern U.S. (9.7 kg/m^2). These differences are due largely to regional differences in the density of residential structures. In particular, we find that A_{res} = 7.5 percent for Davidson County, while A_{res} = 9.7 percent for all U.S. cities and A_{res} = 6.3 percent for the southern United States. Thus, residential Nashville is somewhat more densely built than average for a southern city, but is still less dense than the average U.S. city. (The highest residential building densities in U.S. cities are found in the northeast and the west [Anno et al., 1988]).

A similar weighting of fuel loads for non-residential urban land could also be performed. The densities and types of structures in each commercial and industrial zone could be determined from aerial photographs, maps, and economic census data. Breakdowns of fuel loads for various building types could then be used to derive detailed fuel density estimates for these areas.

3.3 FUEL LOADING MAP.

The fuel loading for the 60 km by 38 km Nashville area shown in Fig. 1 is developed on a 1 km by 1 km grid. (The resolution is arbitrary and limited only by the resolution of the land use maps—i.e., 0.04 km^2 for all urban categories and bodies of water and 0.16 km^2 for all other land use types; a much finer grid could be used). The areal fraction f_i of each grid square occupied by each of the 11 land use categories is determined, and the net fuel load density FD_{net} for the square calculated from

$$FD_{net} = \sum_{i=1}^{11} f_i \cdot (FD)_i \quad . \qquad (5)$$

where $(FD)_i$ is taken from Table 1 for all nonresidential land use categories and FD_{res} is computed as described above. The fuel load map is shown in Fig. 9.

Although the highest fuel loads are located near the downtown area, the distribution around the central city is highly asymmetric. Generally, higher fuel loads follow the distribution of residential land—i.e., along a southwest-to-northeast axis through the city center. The largest loadings (> 40 kg/m^2) are associated with industrial zones and heavy MF residential concentrations. Outside the built-up area, the highest fuel loads are found on agricultural plots (for example, along the Cumberland River west of the city). These results demonstrate the highly uneven distribution of combustible fuels in and around urban areas.

We find that the mean fuel load for the entire map shown in Fig. 9 is 5.0 kg/m^2; for Davidson County, it is 6.9 kg/m^2; and for Nashville proper, 18.9 kg/m^2. Such values are considerably smaller than the approximately 40 kg/m^2 mean usually assumed for cities [Penner, 1986]. Moreover, the distribution of fuel is clearly nonuniform with some (target) areas having substantially greater or lesser than average loadings.

Major bulk liquid fuel storage sites in Nashville are concentrated in the industrial zones along the south bank of the Cumberland near West Nashville. Other sites are located along the river immediately north and south of downtown and at the airport. The most vulnerable of these sites are those in which the products are stored in above-ground tanks easily identifiable in aerial photographs and topographic maps. (In Nashville, these tanks contain only refined products; there are no refineries in the area.) There are 87 above-ground tanks ranging in size from about 18 to 36m diameter with an average capacity of 4550 m^3. Assuming each tank is half full, the estimated total fuel inventory is 197,900 m^3. For a density of 740 kg/m^3 (typical of gasoline), the estimated stored fuel mass is 0.146 Tg. If distributed uniformly throughout Nashville proper (232 km^2), the loading is increased by 0.63 kg/m^2; if distributed over Davidson County (1187 km^2 exclusive of J. Percy Priest Reservoir), the additional loading would be 0.12 kg/m^3. Fuel stored in vehicles[1] and pipelines enhance these values only slightly.

1. We estimate a net gasoline inventory of 0.005 Tg stored in vehicles in metropolitan Nashville assuming 0.67 vehicles per person [U.S. Bureau of the Census, 1986], an average tank capacity of 12 gallons, and each tank half full.

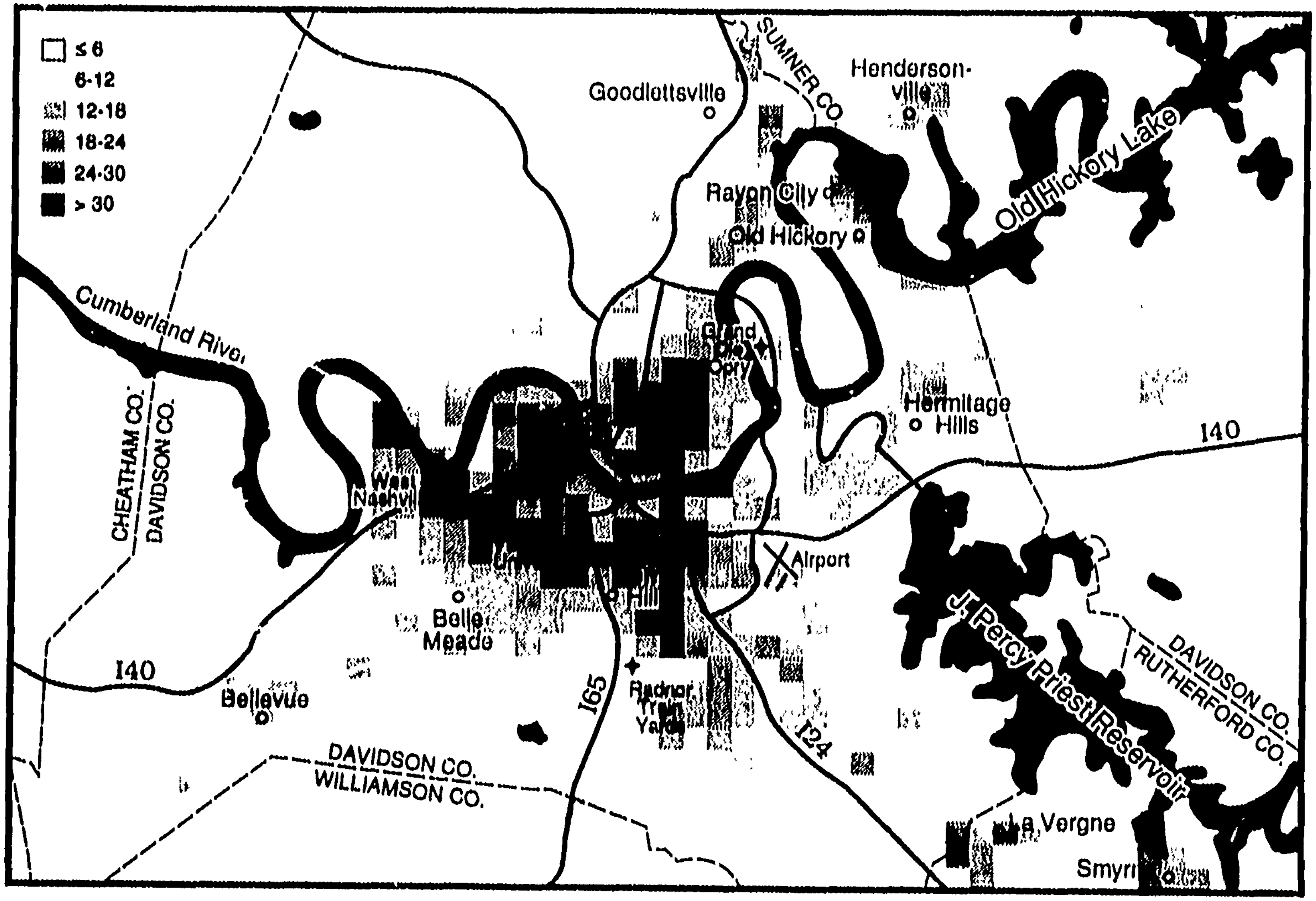


Figure 9. Fuel load density (kilograms per square kilometer), metropolitan Nashville.

SECTION 4

IMPLICATIONS FOR SMOKE INJECTION

To demonstrate how the nonuniform distribution of fuel loads in a city influences the smoke source, we consider area fires collateral to three hypothetical target sites: (1) the Tennessee State capitol (a political target); (2) the Tennessee Air National Guard station (a military site); and (3) the power generating station located at the J. Percy Priest Dam (an economic target). The locations are shown in Fig. 10. Circles of 10-km radius, which define the optimum 3-psi overpressure ignition zone for a 1-MT airburst, are drawn around each target. There is considerable overlap; the maximum distance between any two targets is only 16 km. Yet, despite their proximity, the amount of fuel contained within each target zone is quite different. Figure 11 shows the variation in net fuel amount as a function of radius. Target zone 1 encompasses the most fuel (mean density 18.5 kg/m^2—about equal to the average for Nashville proper) since it lies near the geographical center of the urban area. Target 2, located at the airport near the edge of the built-up area, contains the next highest loading (8.2 kg/m^2), and target 3, near the edge of the city, contains the least (4.4 kg/m^2). Thus, a nuclear burst over target 1 could burn more than four times the fuel of an identical burst over target 3.

These differences in fuel availability affect not only the amount of smoke produced, but also the fire behavior. In Fig. 12 we show the variation in fuel load density FD_{net} as a function of radius for the three targets. Note the strong radial dependence, especially for target zone 1, which encompasses mostly heavily loaded urban land within about 4-km radius and more lightly loaded suburban areas at greater radii. This is quite unlike the idealized uniform fuel load distribution assumed in most smoke plume and nuclear winter calculations. The radial dependence in FD_{net} implies that the fire intensity or duration may not be constant throughout the target area. Since the smoke injection is closely coupled to the burning dynamics, markedly different smoke injections can result even in the same city. Target zones 2 and 3, on the other hand, have a more uniform fuel load distribution which slowly increases with radius as more high-density, built-up land is involved.

The fuel load densities (Fig. 12) have been used to determine the fire plume and smoke injections for each target area. The fire intensity is assumed proportional to FD_{net}, the total burning time is 2 h, and the smoke emission factor (smoke mass generated per unit fuel mass burned) is 0.03. For target area 1, both the smoke generation rate and the heat release rate are greatest between 1- and 4-km. For targets 2 and 3, however, the fuel densities are greatest 10 km from the burst and thus the intensity and smoke production are largest at the fire edge. (We assume a 10-km fire radius for a 1-Mt burst.) A mean July sounding for Nashville was used. The atmosphere was warm and moist at lower levels, and the troposphere conditionally unstable.

Figure 13 shows the simulated smoke plumes associated with targets 1 and 3 after 2 h. (The complete set of results is presented in Heikes et al., 1989.) Clearly, the difference in the amount of fuel contained in these target zones has a dramatic impact on the plume. With the relatively low and uniform fuel loads

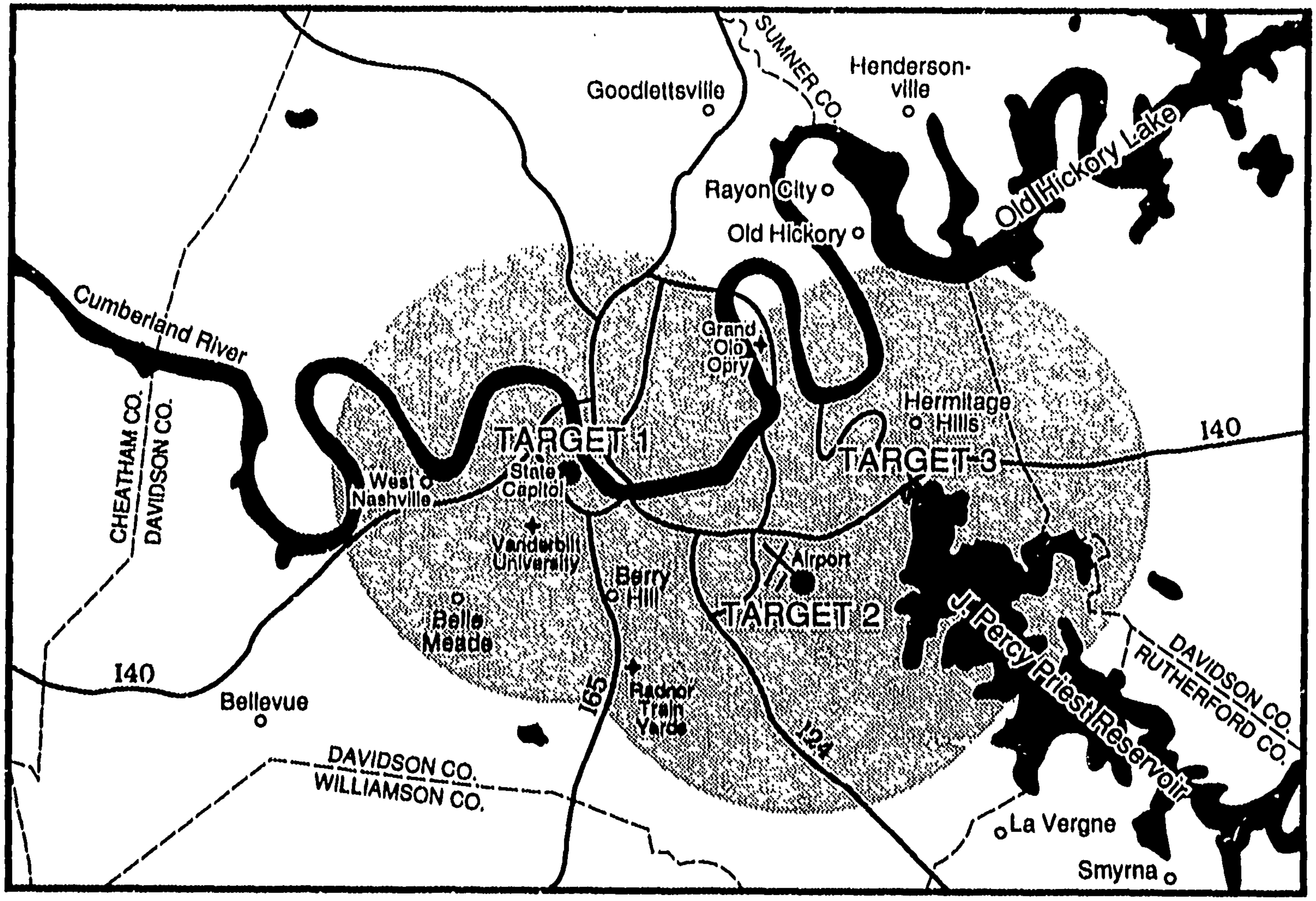


Figure 10. Hypothetical targets, metropolitan Nashville.

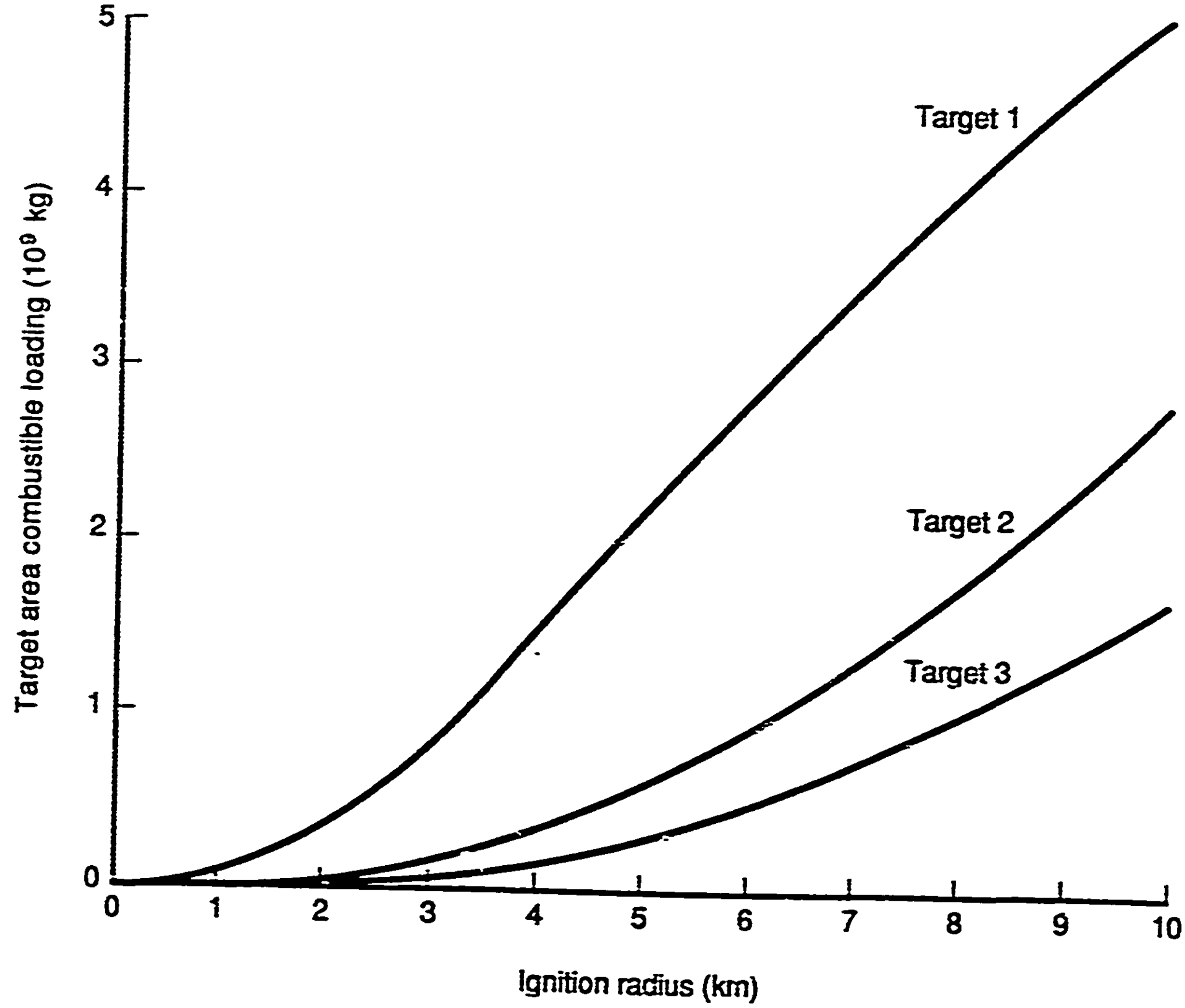


Figure 11. Cumulative fuel mass for three targets.

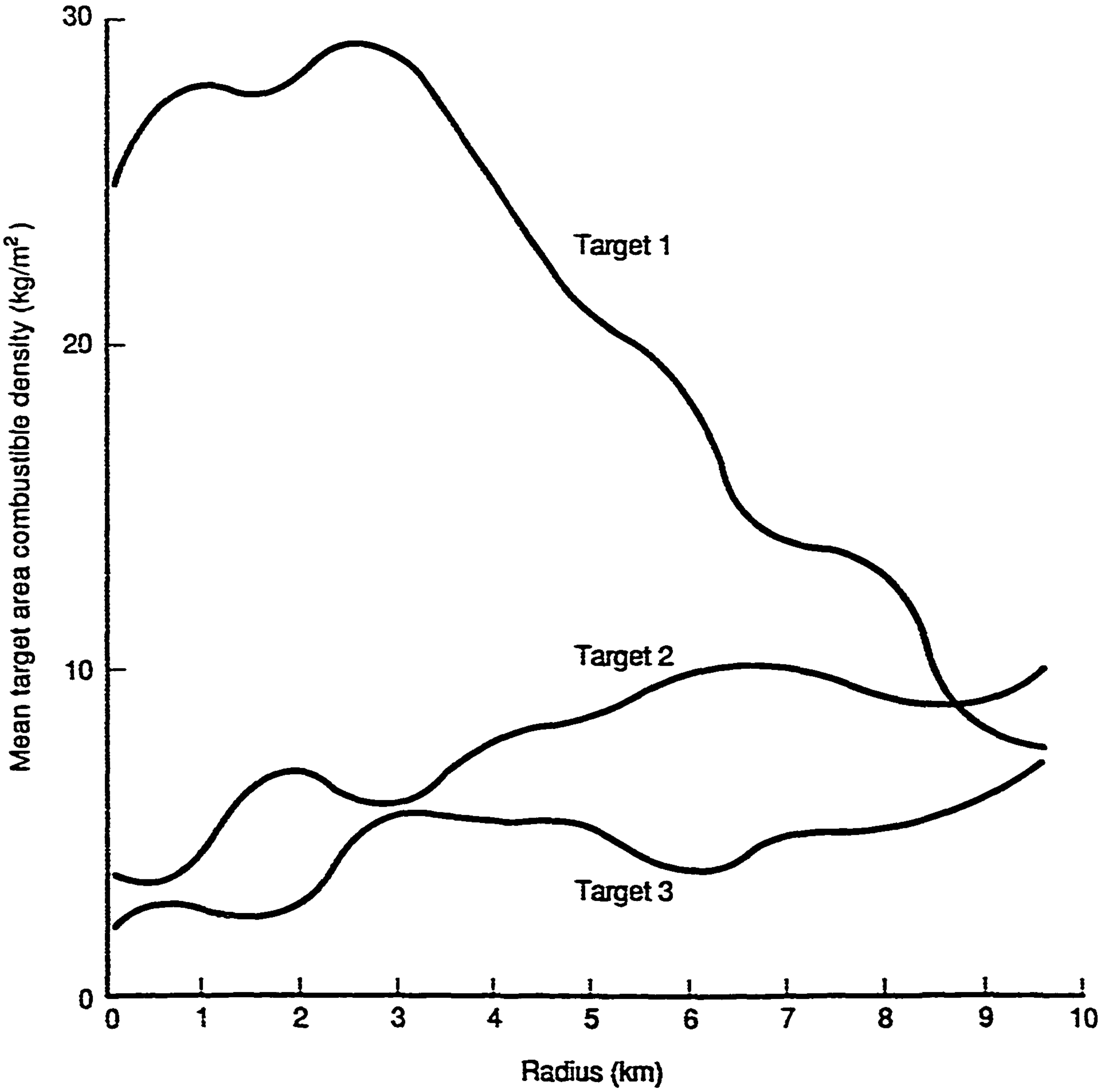


Figure 12. Fuel load density as function of radius for three targets.

associated with target 3, the plume remains confined to the lower troposphere and spreads radially at about a 3-km altitude (Fig. 13a) despite the conditionally unstable sounding. The target 1 loading, however, produces a plume that develops explosively in the conditionally unstable atmosphere, penetrates the tropopause at 15 km, and extends far into the stratosphere (Fig. 13b). The difference is due not only to the greater fuel availability in the target 1 burning zone, but also to its heavy concentration near the center. This increases the heat release rate near the middle of the fire and provides the plume with enough buoyancy (and therefore momentum) to penetrate to very high altitudes. Clearly, the behavior of the smoke plume is highly sensitive to the target locations in and around the city.

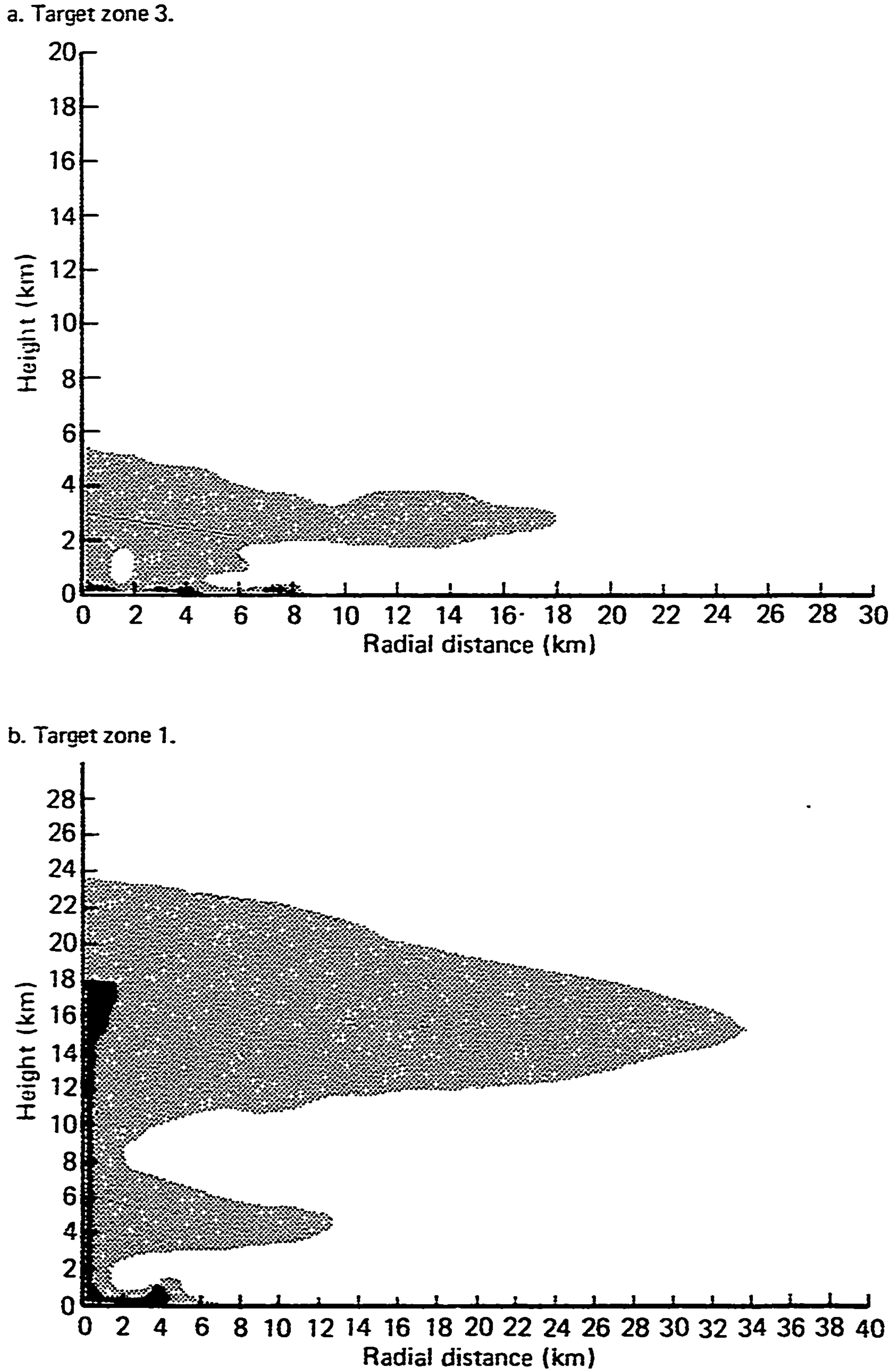


Figure 13. Simulated smoke plume after 2 h for two target zones.

SECTION 5

CONCLUSIONS

We have estimated the combustible fuel loads for metropolitan Nashville. Tennessee using land use and census data. Nashville's fuel loads are not uniformly distributed and are highly dependent on the internal structure of the city. The highest fuel load densities are found in portions of the city occupied by densely packed multiple-family housing structures. hydrocarbon storage terminals. and in industrial/commercial complexes. The nonuniformity of the fuel distribution results in a several-fold difference in the net fuel availability for targets spaced only a few kilometers apart. This in turn strongly influences the intensity of nuclear weapon fires. the amount of smoke emitted. and the altitudes to which the smoke is injected.

SECTION 6

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